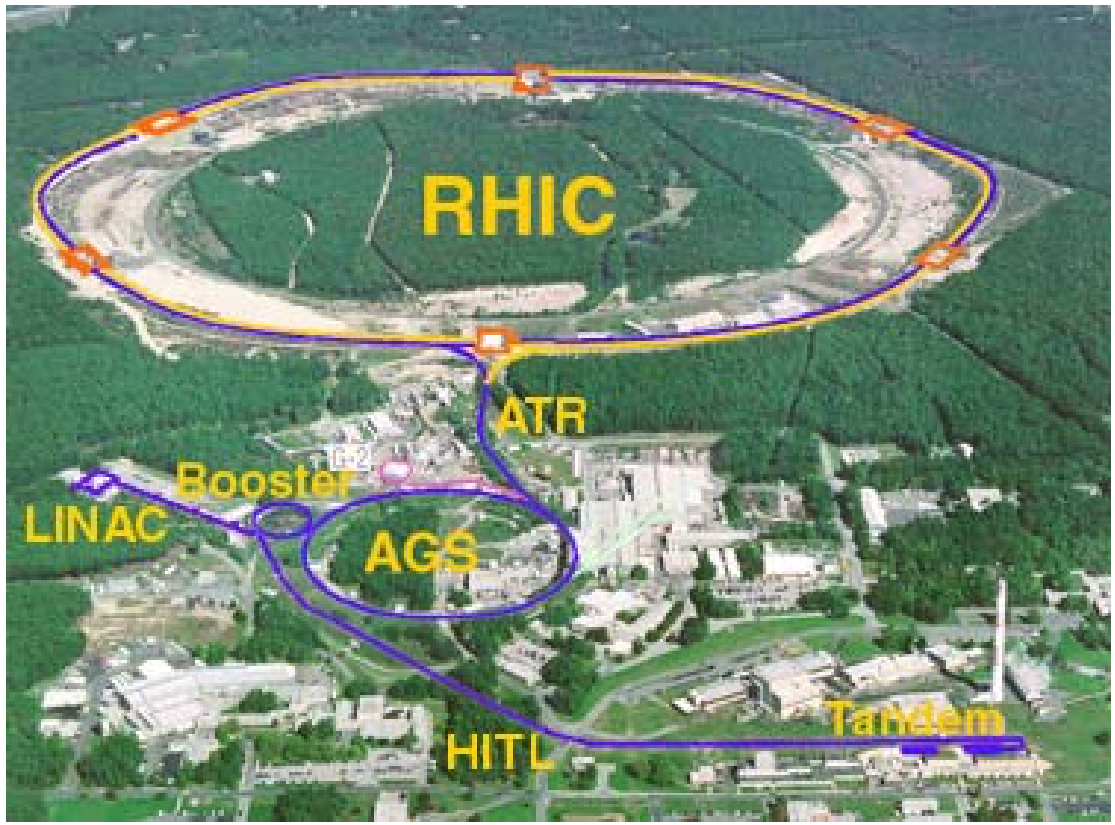
New Phenomena at RHIC

Are we seeing
Quark Matter?



T. Ludlam
Pheno 2003
Madison, Wisconsin
May 2003

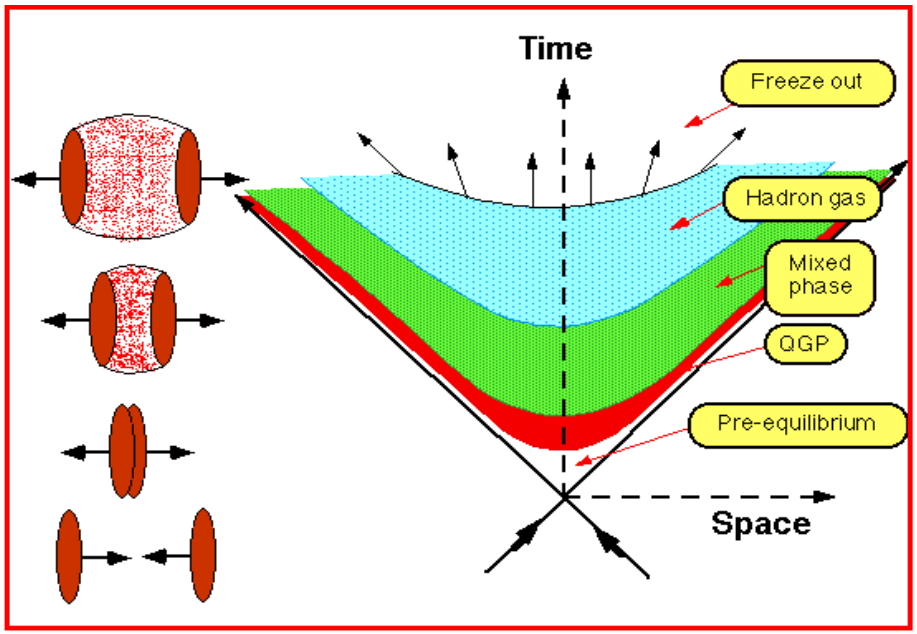
STAR

BROOKHAVEN
NATIONAL LABORATORY

A Mini-Bang:

Nuclear matter at extreme temperatures and density

Colliding nuclei at 100 + 100 GeV/nucleon



a. **Formation phase -**
parton scattering

b. **Hot and dense phase -**
quark-gluon plasma and hadron gas

c. **Freeze-out –**
emission of hadrons

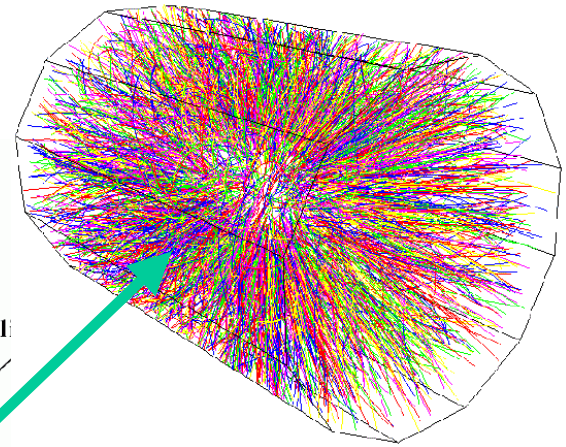
Produce and explore a new state of matter-- quark-gluon plasma

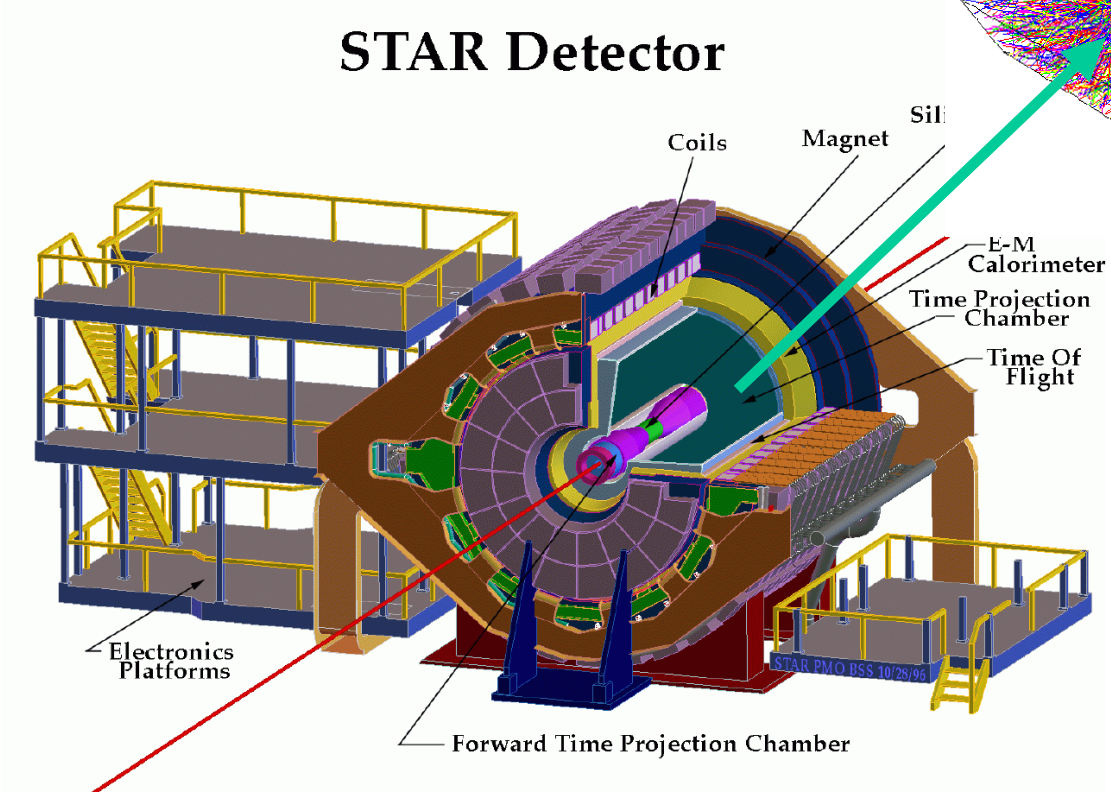
Excite the QCD vacuum on a large scale

STAR : The "Visual" Imaging Detector

- 0.5T Solenoidal Magnet
- Time Projection Chamber…
  - 2m radius x 4m long;
  - 140,000 pad readout x 512 time samples
  - dE/dx in 1 atm. P-10 gas
  - total drift time = 40 μS
- Silicon Vertex Tracker
- Electromagnetic Calorimetry

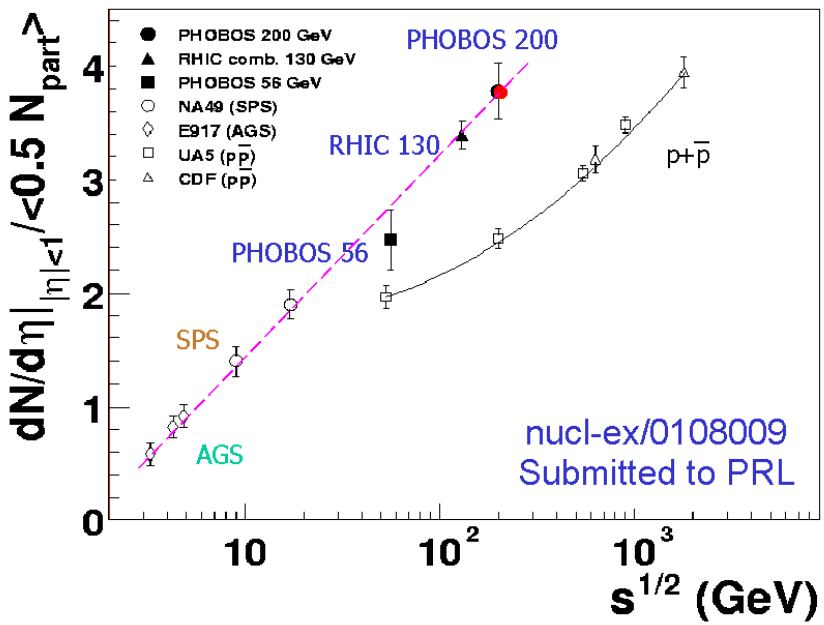
Central Au-Au collision in the Time Projection Chamber

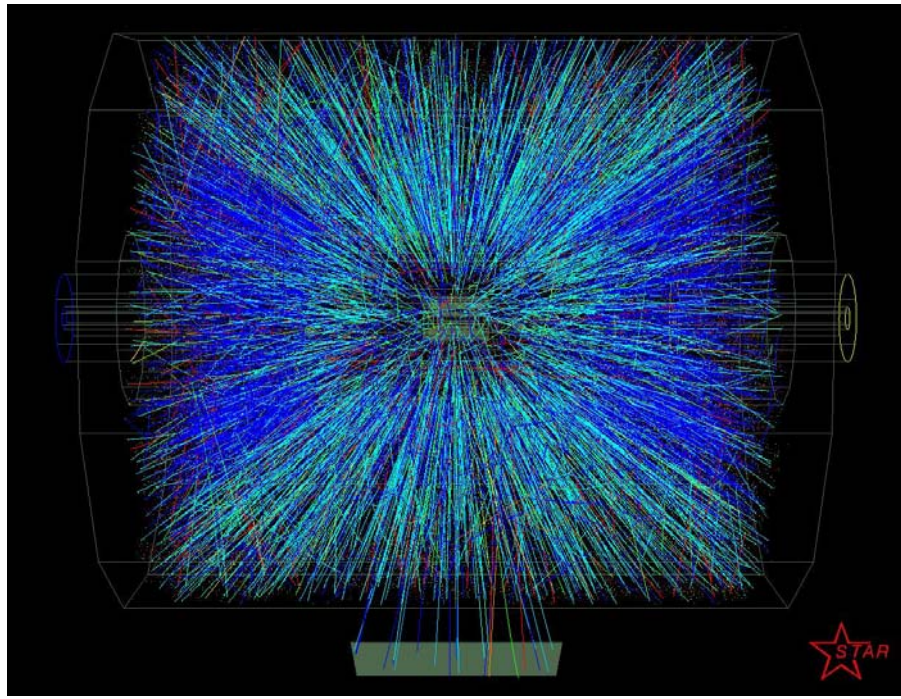




Central Au-Au collision: A Mini-Bang?

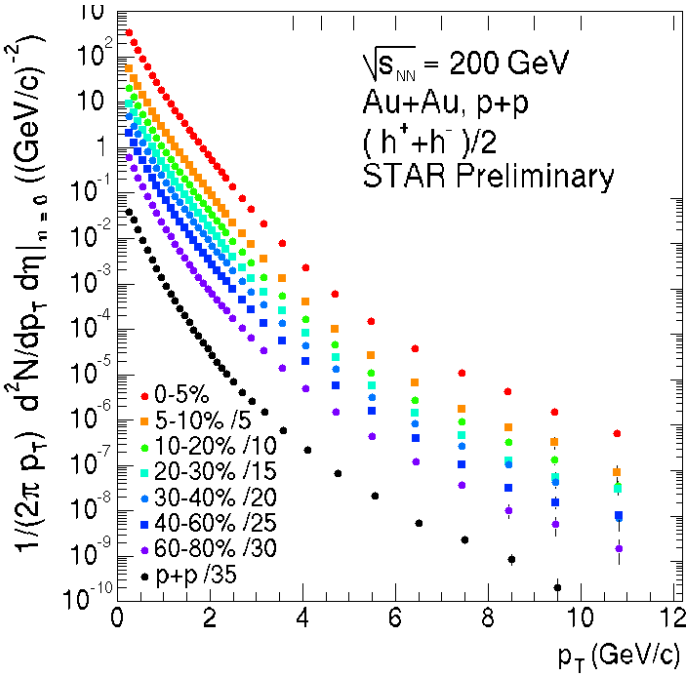
$dN_{ch}/d\eta|_{|\eta|<1}$ vs Energy

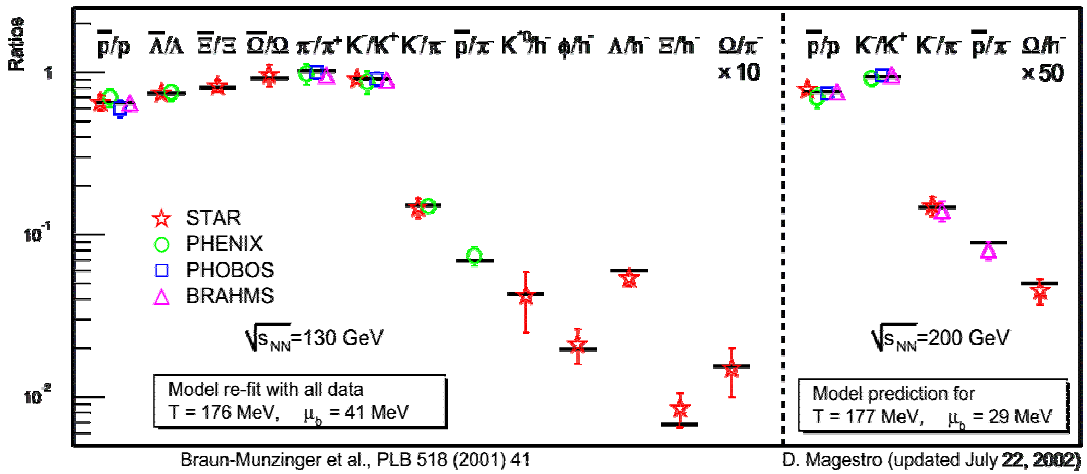




Initial energy density >10 GeV/fm^3 over a volume of ~1000 fm^3

What can we measure?





Braun-Munzinger et al., PLB 518 (2001) 41

D. Magestro (updated July 22, 2002)

Particle spectra to high p_T, as function Of centrality (impact paramter)

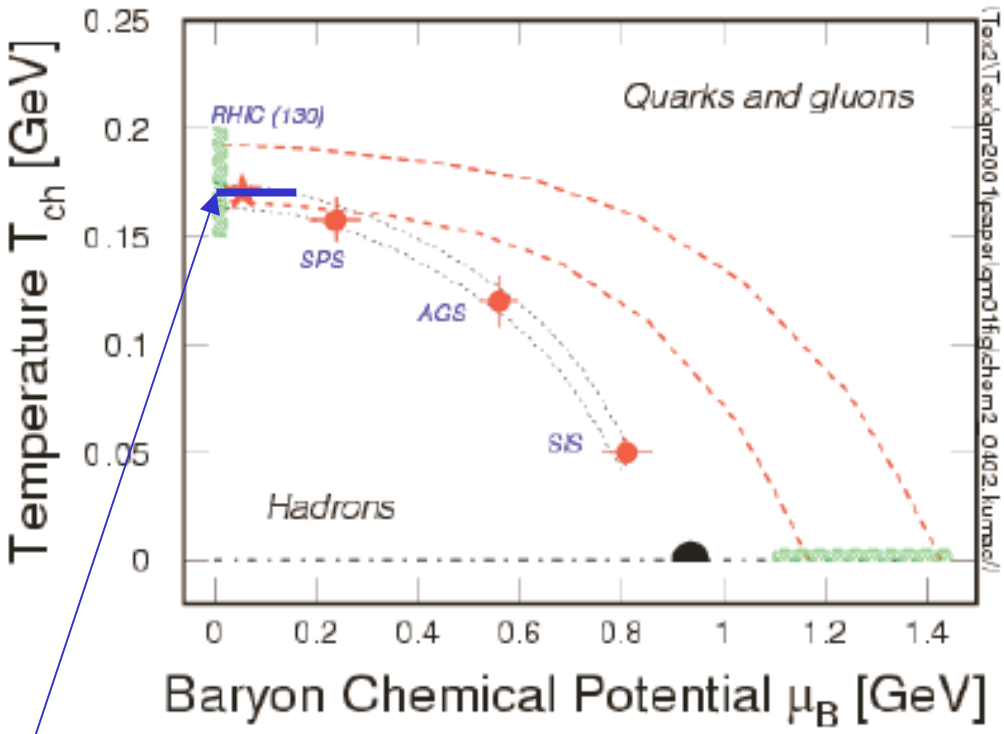
pp collisions, in RHIC, for comparison With Au-Au

Particle ratios fit to thermal model:

Temperature ≈ T_C from lattice QCD calculations

Baryon chemical potential approaching zero

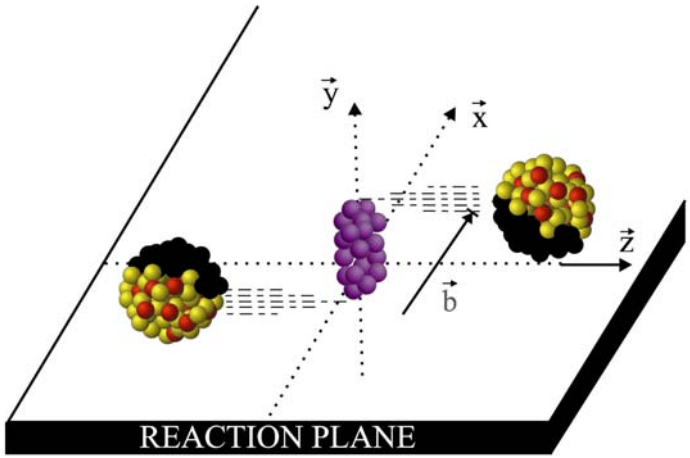
Thermodynamics of strong matter

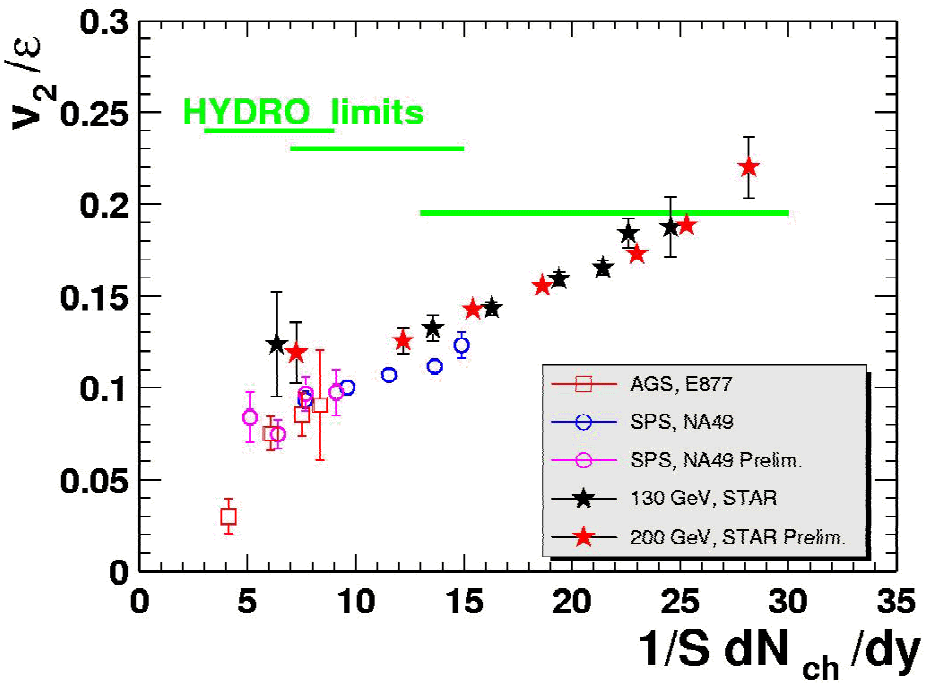


- It's hot enough…
- It's dense enough…
- Is it "matter" (thermal)?
- Is it "quark matter" (partons in thermal equilibrium)?

Lattice QCD Phase Boundary
Z. Fodor and S.D. Katz
nucl-th/0201071

“Flow” in hot QCD matter





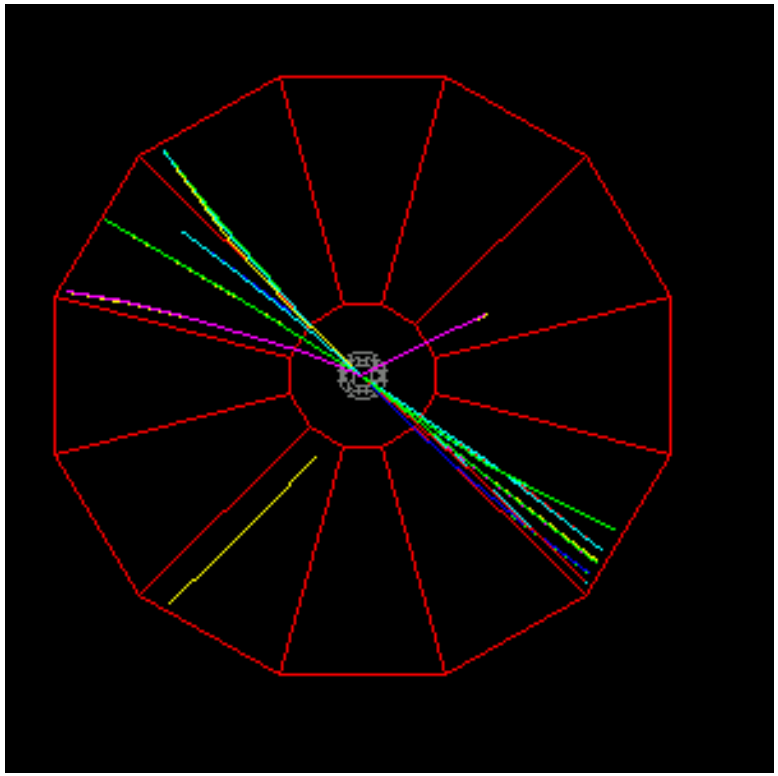
Directed Flow Elliptic Flow

$$\frac{d^3N}{dp_t\,dy\,d\varphi} = \frac{d^2N}{dp_t\,dy}\frac{1}{2\pi}(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots)$$

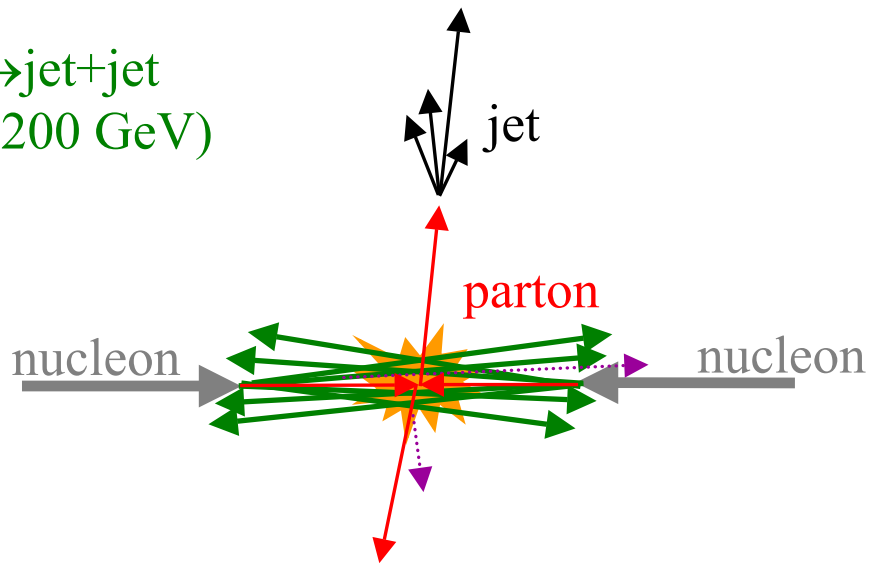
For RHIC collisions with highest particle density in the overlap region:
Elliptic flow approaches the hydrodynamic limit

Hard Scattering at RHIC

cross sections are high!

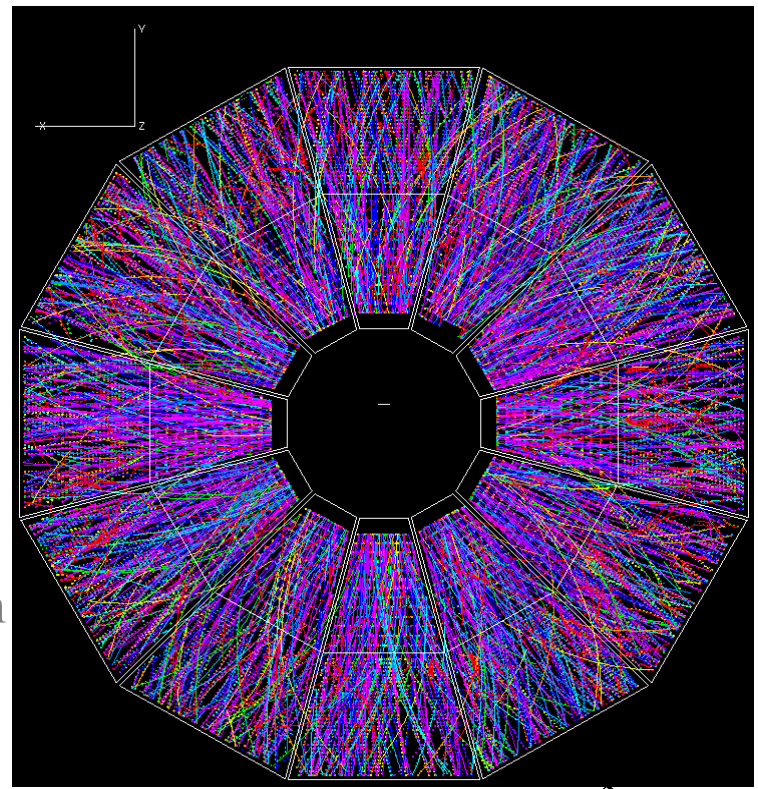


p+p →jet+jet
(STAR 200 GeV)

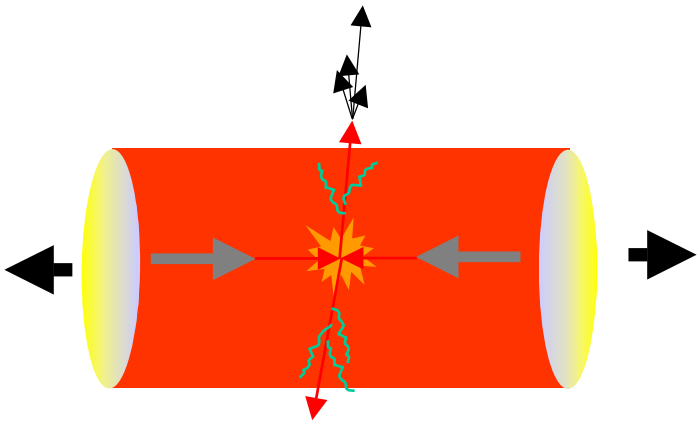


Au+Au →???

(STAR 200 GeV/nucleon)



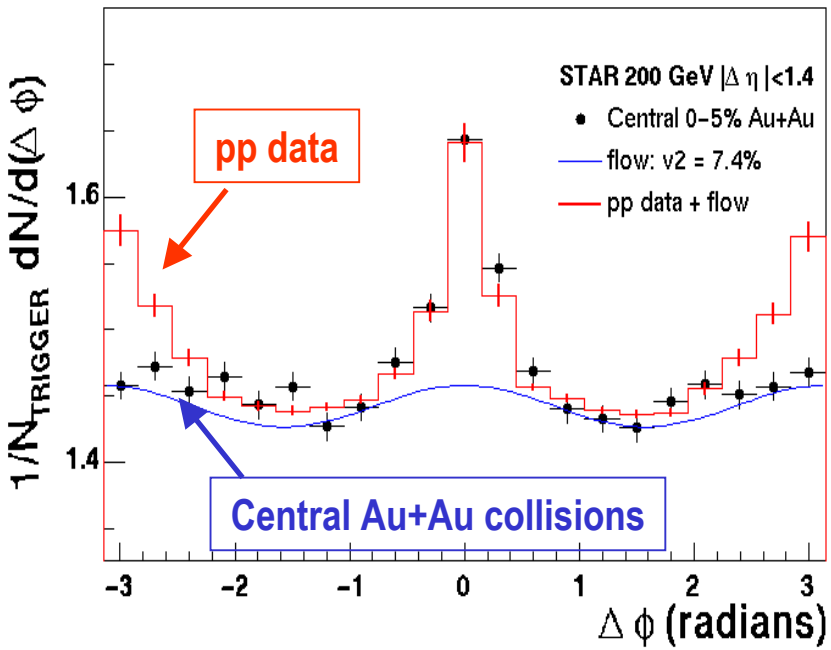
Jet Quenching: a smoking gun?



Gluon Bremsstrahlung:
Jet energy loss in dense matter

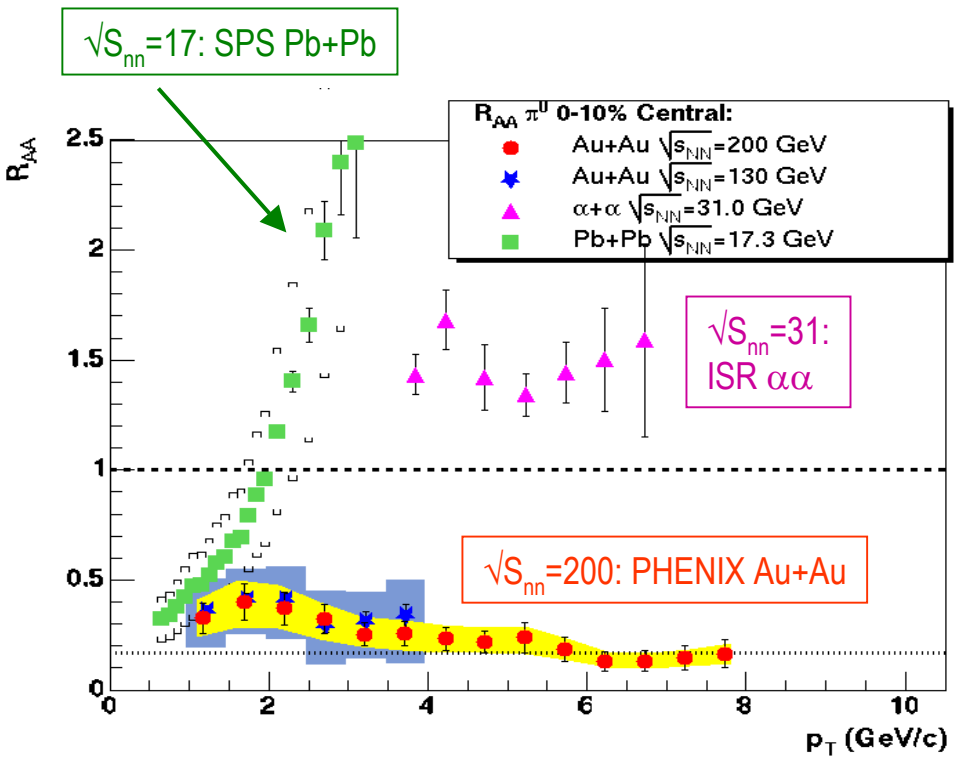
Strong dependence of energy loss on gluon density:
• measure $\Delta E \Rightarrow$ gluon density at early hot, dense phase

STAR two-particle correlations with high p_T trigger particle… recoil jet suppression



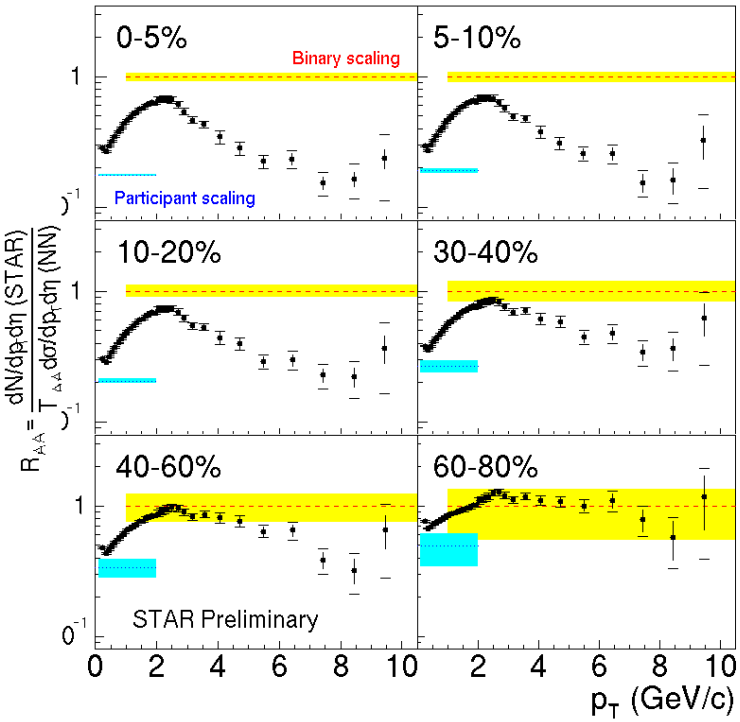
Jet Energy Loss via leading hadrons

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$



Inclusive π^0 in central collisions

√S_nn=200: STAR Au+Au



Charged hadrons:
Dependence on centrality

The importance of deuteron-gold collisions in RHIC

Two opposite theoretical interpretations of the jet quenching results in Au+Au:

1. **Final-state interactions with opaque matter at 100x normal density**
   → **QGP:**
   no jet quenching in d+Au; $R_{AA} \geq 1$

2. **Extreme shadowing (saturation) of the initial-state nuclear wave function**
   → **Shattered Color Glass:**
   Jet quenching persists in d+Au; $R_{AA} \leq .7$

d+Au run was completed in March: results due soon

What have we learned from RHIC collisions?

- Initial energy density > 100 x normal nucleus
- Strongly interacting matter…

  Thermalization: $\tau \leq 1$ fm/c → freeze-out: $\tau \sim 10$ fm/c
- Freeze-out volume ≈ 1000 fm^3
- Temperature of thermal volume T > 200 MeV
  - To be compared with lattice gauge: $T_{critical} = 175 \pm 10$ MeV

All point to the formation of hot, dense, deconfined matter, i.e. QGP

- Suppression of high p_T hadrons → extreme parton density in early stages
- d+Au should soon resolve whether the action is in the final state (QGP); or initial state (Color Glass Condensate)

The landscape of nuclear collisions at RHIC is no longer *Terra Incognita*

Next Steps

- Pin down further signatures of the quark-gluon plasma and associated phase transitions…. For example:
  - The role of heavy quarks – color screening in J/psi, Upsilon spectra
  - Effects of chiral symmetry restoration – distortion of low-mass resonances
  - Onset of deconfinement and mixed phase – energy and volume scans

- Explore the early phases of reaction dynamics in QCD matter formation…
  - Jet tomography – photon-tagged jets

- Determine the properties of bulk QCD matter
  - Equation of state of quark gluon plasma
  - New phenomena -- Strong CP violation?
    Disoriented chiral condensates?

- Extended studies of partonic contributions to nucleon spin structure
  - RHIC spin program with polarized proton collisions with $\sqrt{S}$ to 500 GeV

Overview of the RHIC Physics Run Plan

Year	Run Plan	Physics
2000	Au-Au at 130A GeV	First look at HI collisions at in the new energy range
2001–2002	Au-Au at 200A GeV Comm./run pp at 200 GeV Au-Au at low E: 19A GeV	Global properties; particle spectra; first look at hard scattering. Comparison data and first spin run Global connection to SPS energy range
2003	d-Au at 100A GeV pp at 200 GeV	Comparison data for Au-Au analysis; low-x physics in cold nuclear matter Spin run/Commission rotators
2004	Au-Au at 200A GeV pp at 200 GeV	"Long Run" for high statistics, rare events Spin Run/Commission jet target
2005	Si-Si/Cu-Cu at 100A GeV pp at 200 & 500 GeV	Comparison studies: surface/volume & impact parameter effects First "full capability" spin run
2006-2010	Long Au+Au, p+p, p(d)+Au pp at 200 & 500 GeV	High-statistics runs with upgraded detectors and luminosity. Explore hot QCD matter with rare probes: Open Charm, Beauty, tagged jets Extended study: nucleon spin structure